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ScienceDirect
Nuclear Instruments and Methods in Physics Research B 261 (2007) 727–730
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Swift-heavy ion track electronics (SITE)

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Available online 27 March 2007

Abstract

An overview about the state-of-art of the development of a new type of nanoelectronics based on swift-heavy ions is given. Polymeric as well as silicon-based substrates have been used, and both latent and etched ion tracks play a role. Nowadays the interest has shifted from simple scaling-down of capacitors, magnets, transformers, diodes, transistors, etc. towards new types of ion track-based structures hitherto unknown in electronics. These novel structures, denoted by the acronyms "TEAMS" (*t*unable *e*lectrically *a*nisotropic *m*aterial on *s*emiconductor) and "TEMPOS" (*t*unable *e*lectronic *m*aterial with *p*ores in *o*xide on *s*emiconductor), may exhibit properties of tunable resistors, capacitors, diodes, sensors and transistors. Their general current/voltage characteristics are outlined. As these structures are often influenced by ambient physical or chemical parameters they also act as sensors. A peculiarity of these structures is the occurrence of negative differential resistances (NDRs) which makes them feasible for applications in tunable flip-flops, amplifiers and oscillators.
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PACS: 61.82.−d; 71.20.Rv; 73.63.−b

Keywords: Ion tracks; Electronics; TEMPOS structures; Negative differential resistances

1. Introduction

There exist a number of competing approaches towards nanoelectronics, e.g. (a) the use of self-organizing nanostructures, (b) molecular electronics, (c) nanomanipulations and (d) nanolithography. All these techniques are excellent strategies, but some (a, d) restrict to relatively few useful systems and others (b, c, d) are time consuming, expensive, and very difficult to realize. In contrast, the idea of using (preferentially: non-overlapping) ion tracks as the main tool for the envisaged purpose, denoted by us as "Single Ion Track Electronics" or "Swift-heavy Ion Track Electronics (SITE)", is simple, fast and cheap to realize ($\sim 10^{-10}$ $ per individual track); the method is precise, and it has a high variability in regard to the parameters governing this technology.

The basic concept of SITE is depicted schematically in Fig. 1. After it had become known that one can produce extended nanopores in a number of insulators by etching tracks of swift-heavy ions therein, the idea arose to fill up these tracks with some (semi) conducting material, to produce (semi) conducting nanowires or nanotubules therein. Regarding the variability of SITE, one has the following range of possibilities:

- The *host materials for tracks* can be insulators as well as semiconductors. Upto now polymers, SiO_2, SiON, organometals, C_{60} and SnO_2 were used.

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0168-583X/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.nimb.2007.03.018

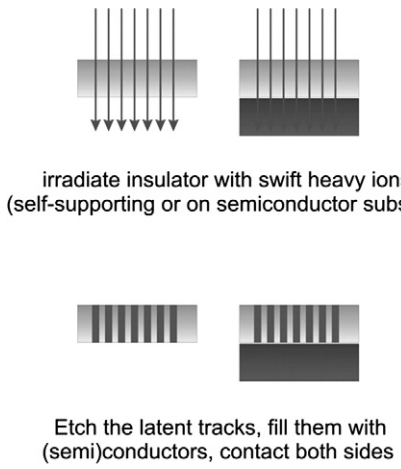
irradiate insulator with swift heavy ions
(self-supporting or on semiconductor substrate)
Etch the latent tracks, fill them with
(semi)conductors, contact both sides

Fig. 1. The basic concept of the swift-heavy ion track electronics (SITE).

- The electronic devices can either be self-supporting, or they can be deposited on some *substrate* such as Si, glass or metal (Fig. 1). Specifically, the deposition of the ion tracks on silicon allows one to create hybrid electronic structures which can be combined with "classical" electronic elements.
- The *track type* can either be latent or etched tracks.
- Etched tracks can have conical, cylindrical, funnel-like, etc. *track shapes*.
- One can deposit various *materials* within the etched tracks, such as metals, semiconductors, liquids or solid electrolytes. Some of the materials used so far were Ag, Au, Pd, Ni, C_{60}, nanographite, CNTs, Phthalycyanine, SnO_2, TiO_2, organometals, conducting polymers and chalcogenides such as CdS, PbS, etc.
- The material deposited within the etched tracks can have various *structures* such as single crystalline, polycrystalline, or amorphous; it can be a gel or a liquid, and one can deal with dispersed nanoparticles or nanoparticle/polymer composites.
- The material deposited within the etched tracks can be arranged in various *shapes* such as wires or tubules; the shape can also be axially or radially structured.
- The *track density* can vary between low (i.e. well separated individual tracks) and high (i.e. overlapping tracks).

After the first feasibility studies of SITE structures had been performed successfully, the fabrication of common active and passive electronic structures such as wires, resistors, batteries, diodes, LEDs and simple sensors using these etched tracks was reported. By combining ion track lithography, etching, material's insertion into etched tracks and evaporation techniques, more complex structures such as capacitors, magnets and transformers could also be made in miniaturized scale [1].

2. TEAMS and TEMPOS structures

Apart from the above-mentioned electronic elements, there are a number of novel multiparametric ion-track-based electronic structures hitherto unknown in classical electronics. In the so-called "TEAMS" (*t*unable *e*lectrically *a*nisotropic *m*aterial on *s*emiconductor) structures, anisotropic (semi) conducting material is deposited onto semiconducting substrates, and these structures are then contacted on their front and back sides [2]. Swift-heavy ion (SHI) irradiation is a good tool to impose electronic anisotropy onto various semiconductors or insulators. Here, the anisotropy is induced by radiochemical reactions or phase transitions (such as polysilane $\rightarrow$ SiC, organometal $\rightarrow$ metal, diamond $\rightarrow$ sp^2 enriched carbon, etc.) along the tracks of SHIs in the corresponding materials.

Alternatively, in a number of insulators (such as SiO_2, SiON, etc.) the material's chemical stability is greatly reduced along SHI tracks, so that chemical etching exposes parallel long narrow pores, the so-called "etched tracks". Filling these pores with (semi) conductors creates (semi) conducting nanowires which make the corresponding insulators anisotropically conducting along the track direction. TEAMS structures built up of such materials have been denoted as "TEMPOS" (*t*unable *e*lectronic *m*aterial with *p*ores in oxide on *s*emiconductor) structures [3–8]. Metallic and semiconducting nanoclusters (NC) are of special interest as fillers in the etched tracks due to their peculiar electronic properties and also because one can arrange them in complex sub-structures. Growth of carbon nanotubes in TEMPOS structures enables the expansion of SITE to electronic 3D architectures.

The current/voltage characteristics of TEAMS and TEMPOS structures are primarily determined by the band transition at the interface between the anisotropic material and the semiconducting substrate which leads to diode-like characteristics. The change of these characteristics by additionally applied gate voltages depends essentially on the ratio of surface conductivity to track conductivity and on the doping of track and substrate.

Charge carrier traps within a single track regime, as well as the interaction of neighbouring nanowires with each other, may lead to negative differential resistances (NDRs). Depending on the materials used for insertion in tracks, ambient physical or chemical parameters such as temperature, pressure, light, magnetic fields, moisture, alcohol, ammonia, etc. may influence the characteristics, so that one can construct multiparametric sensors.

3. Negative differential resistances

Negative differential resistances (NDRs) usually emerge from pulsed charge transfer, when in a system a suddenly increasing current leads to the rapid breakdown of the applied voltage. Such NDRs are found in arc discharges, and they are the characteristic properties of Esaki (or double-base) diodes and unijunction (or filamentary) transistors. One of the possible reasons for the emergence of NDRs in electronics is the decrease of the electric resistance with increasing current due to positive temperature coefficients, coincident with the electronic system being unable

to supply the additional charge required for maintaining the originally applied voltage. Once the voltage breakdown has occurred, the system may gradually recover towards the originally applied voltage until another breakdown process occurs. (Please note that vice versa, not every pulsed current leads to NDRs.) NDRs are also often found in TEMPOS structures. It appears that we can distinguish here two different types of NDRs, the ones which emerge along individual tracks and the ones which result from the interaction of tracks with each other.

3.1. NDRs of individual tracks in TEAMS and TEMPOS structures

The ion tracks in a TEAMS structure are not only zones of enhanced conductivity but also regions of radiation damage. Damage centers are known to act as transient traps for charge carriers with bonding energy E_{trap}, as do intrinsic defects. These traps can be described as resistors R_{trap} in parallel with capacitors C_{trap}. Let us assume for simplicity that for an externally applied voltage $U < E_{trap}$: $R_{trap} = \infty$, and that for $U > E_{trap}$, R_{trap} becomes very small: $R_{trap} = R_0 \to 0$, i.e. the charge carriers are either bonded or free. These resistors R_{trap} are parallel to some resistance R_{bulk} describing the current fraction outside the tracks, which is not trapped at the defects. To this total sample resistance $R_{sample} = (R_{trap}^{-1} + R_{bulk}^{-1})^{-1}$, the resistance R_{ext} of the external electric circuit has to be added: $R_{total} = R_{ext} + R_{sample}$. This means that in whatever state of the radiation-induced traps – active or inactive – there is always some current flowing. In case of $U < E_{trap}$ that current is $I_{bulk} = U/(R_{ext} + R_{bulk})$.

For $R_{trap} = \infty$, the applied voltage $U < E_{trap}$ leads to the accumulation of a charge $Q = C_{trap}\, U$, with C_{trap} being the capacitance of all traps. When $U > E_{trap}$, i.e. $R_{trap} = 0$, the track capacitor discharges, with a discharge current $I_{disch} = -\mathrm{d}Q/\mathrm{d}t = C_{trap}\, \mathrm{d}U/\mathrm{d}t = U/R_0$ adding to the current I_{bulk}. R_0 describes macroscopically the resistance of the traps. Hence, $Q/C_{trap} = -R_0\, \mathrm{d}Q/\mathrm{d}t$. The solution of this differential equation is $Q = C_{trap}U_0\ \exp(-t/(R_0C_{trap}))$, consequently $I_{disch} = \mathrm{d}Q/\mathrm{d}t = U_0/R_0\ \exp(-t/(R_0C_{trap}))$.

This current releases the overall charge Q stored in all traps along the tracks. The rapid discharging leads to a rapid change of the voltage along the traps: $-\mathrm{d}U/\mathrm{d}t = C_{trap}^{-1}\ \mathrm{d}Q/\mathrm{d}t = U_0/(R_0C_{trap})\ \exp(-t/(R_0C_{trap}))$, hence the voltage itself is $U(t) = U_0\ (1 - \exp(-t/(R_0C_{trap})))$. As long as R_{ext} is large enough so that this voltage drop is not compensated immediately by the external voltage supply, the effective resistance of the equivalent circuit can be described by $R_{eff}(t) = U(t)/I(t) = -R_0(1 - \exp(-t/(R_0C_{trap}))$. This signifies that the effective trap resistance during the buildup of the discharge current is initially negative, and then rises exponentially until it obtains positive values, Fig. 2(a).

The discharge current will not rise forever but gradually come to saturation. To describe this situation let us differentiate $Q = C_{trap}U$, to obtain $\mathrm{d}U/\mathrm{d}t = -1/C_{trap}\ \mathrm{d}Q/\mathrm{d}t = -I/C_{trap}$; hence $I = C_{trap}\ \mathrm{d}U/\mathrm{d}t$. Due to $I = U/R_{eff}$ one has $\mathrm{d}U/\mathrm{d}t = U/(R_{eff}C_{trap})$ with the solution $U(t) = U_0\ \exp(-t/(R_{eff}C_{trap}))$. Due to $I = U/R_{eff}$ the discharge current $I(t)$ decreases now proportionally to the voltage $I(t) = (U_0/R_{eff})\ \exp(-t/(R_{eff}C_{trap}))$. In other words, the effective trap resistance $U(t)/I(t)$ in that second phase, the discharge phase, is positive and constant, Fig. 2(b).

In conclusion, the overall discharge current first rises steeply from $I_{tot} = I_{ext}$ to some maximum $I_{tot} = I_{ext} + I_{disch}$, and thereafter decreases until all the stored charge Q is released. This is accompanied by an initial negative differential resistance which grows rapidly until it reaches a stationary positive value. Theory also predicts that the higher the breakdown voltage, the shorter the time constant of discharge, i.e. the sharper will be the discharge pulse. The smaller R_{ext}, the faster is the voltage recovery of the structure and the shorter the pulse sequence; however, for too low R_{ext} the external voltage source will replace the missing charge in the sample so rapidly that current pulsation is avoided and the resistance remains positive and stable.

As an example of the above model, recent results on SnO_2-TEAMS where pronounced NDRs after ion irradiation were found are shown in Fig. 3(c). As the deep traps created after swift-heavy ion irradiation are only

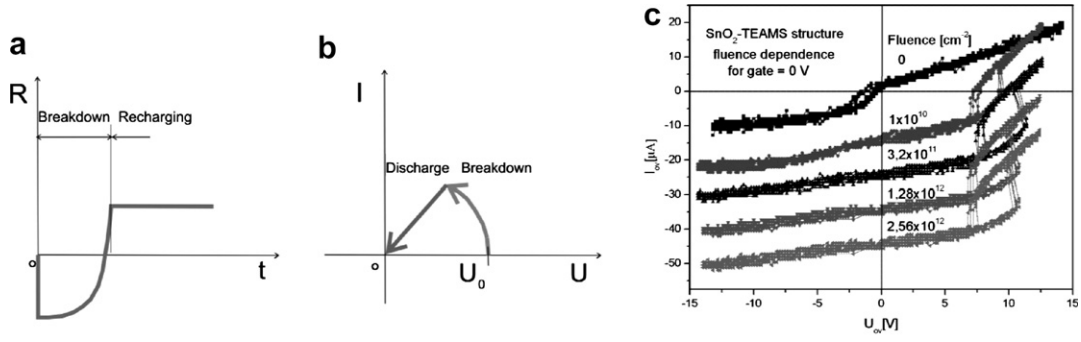

Fig. 2. (a) Time dependence of the resistance and (b) current/voltage correlation of structures with NDRs; schematic sketch. (c) Current–voltage characteristics with NDRs of SnO_2-TEAMS after swift-heavy ion irradiation. For better visibility, the individual curves are replaced by −10 μA to each other.

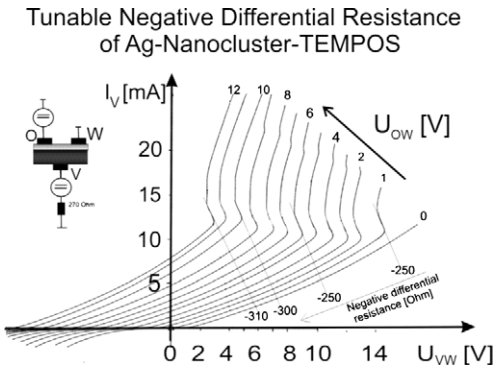

Fig. 3. Current/voltage correlation of a TEMPOS structure with NDRs.

meta-stable at room temperature, the observed NDRs vanished after some time.

3.2. NDRs after collective track interaction in TEAMS and TEMPOS structures

Not all NDRs observed in TEAMS or TEMPOS structures can be explained in the above manner; occasionally it is inevitable to assume some collective interaction process to take place. For example, let us consider a TEMPOS structure of *p*-Si substrate with a SiON layer over it, and for simplicity only two tracks embedded. Let us also assume that the tracks are filled with dispersed metallic nanoclusters, and that the tracks are contacted by contacts o and w each. Suppose one applies a negative voltage at contact o, and a positive voltage at contact v. Then the diode below contact o, formed by the embedded track and the silicon substrate, is open. Consequently an Ohmic current flows from v to o. As long as only low positive voltages are applied at the bottom contact v (see inset of Fig. 3), the voltage below track w is negative, hence the track diode D_w at contact w is reverse biased. With the voltage at v increasing, the voltage drop below w becomes positive so that the diode D_w becomes conducting. This leads to a hole injection into the neighbouring *p*-Si region, hence to the reduction of the resistance R_w of track w. Therefore, the positive voltage above w increases, and more holes are injected via the diode D_w. This process continues until the resistances R_w and R_o vanish. In this case the total current through the structure increases dramatically and is limited only by the resistance of the diode and of the external circuit. In other words, the structure has switched from high Ohmic to low Ohmic state. This rapid charge loss leads to a voltage breakdown, hence to a NDR. This property can be used to design flip-flops, amplifiers and oscillators.

4. Summary

Swift-heavy ion track electronics (SITE) is one of the possible strategies towards future nanoelectronics. In SITE, there exist specific track/Si hybrid structures TEAMS and TEMPOS structures not known in conventional electronics. Their ability to combine with nearly any material opens a vast field of sensing applications. If these TEAMS/TEMPOS sensors are operated in the NDR mode, the emergence of smallest-scale intelligent sensors appears feasible.

Acknowledgement

One of us, A.C., wishes to acknowledge the financial support given by the Alexander von Humboldt Foundation, Bonn, Germany and the Hahn Meitner Institute, Berlin, Germany.

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